L. B. Ham

An Investigation of the Acoustical Galvanometer

AN INVESTIGATION OF THE ACOUSTICAL GALVANOMETER

BY

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THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY LLOYD BLINN HAM

ENTITLED AN INVESTIGATION OF THE ACOUSTICAL GALVANOMETER

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARTS

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*Required for doctor's degree but not for master's

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I INTRODUCTION

The construction of the acoustic galvanometer suggested itself to Professor F.R. Watson in the course of an investigation of the intensity of sound. A Rayleigh resonator was used to measure the sound and its action was such that it seemed probable that it would respond if the sound from a telephone receiver was substituted for the external sound waves in air. On trial, this prediction was confirmed, so that the modified instrument gave responses that were due primarily to the current actuating the telephone receiver; that is, it gave a measure of the alternating current.

The purpose of this work was to investigate the action of the instrument under different conditions, to determine its range of sensitiveness and ascertain its possible use in various measurements.

II HISTORICAL

Lord Rayleigh (Scientific Papers Vol.II, Art.79, p 6) when attempting to find the cause for the eccentric action of a galvanometer, discovered that the suspended mirror was deflected by sound waves. The deflection was intensified by the galvanometer cover which acted as an acoustic resonator.

This discovery suggested to him the desirability of using a similar device for the measurement of sound. (Lord Rayleigh, Phil. Mag. Vol.14,p 186, 1882). Thus, a rotating mirror with attached magnets was suspended by a silk thread in a brass tube, the deflections of which were noted by a reflected beam of light on a scale S. The essential parts are shown in Fig.1, where the brass tube is represented by CE, the rotating disc by D, the lens by L, the glass plate by BC, and the scale by S. It is desirable to have a paper diaphragm at the node N to keep the suspended parts protected from

accidental currents of air. This will offer but little obstruction to the sound.

The greatest response to sound will be obtained when the sound entering at E will set up stationary waves such as to have a node at one-third the length of the tube from E and a loop at the point of suspension D, two-thirds of the distance from E. This subjects the suspended disc (Fig.2) to a turning couple, pp, due to the alternating currents of air so that it tends to turn to a position at right angles to the stream (Barton, "Text-Book on Sound",Sec. 283).

The principle involved here may be applied to a more complicated form of instrument to be described in turn.

III THEORETICAL

As long as we keep to the single resonator, the theory remains quite simple and is fundamental to the understanding of the action of the resonator.

For the single resonator, Barton ("Text-Book on Sound", Sec.94) shows that the sharpness of resonance or sensitivity to tuning depends upon the damping factor. This, in turn, is small for a small opening. Assuming a small opening and no damping, the equation of motion is

$$m\frac{d^2y}{dt^2} + sy = 0$$

where the mass of air in motion is represented by m, and the displacement by y, and the spring factor, or force per unit displacement, by s. A solution of this equation shows that $\omega (=2\pi \div \tau)$ is

$$\omega^2 = s/m$$

or the period, τ , is

$$\tau = 2\pi\sqrt{m/s} \qquad (1)$$

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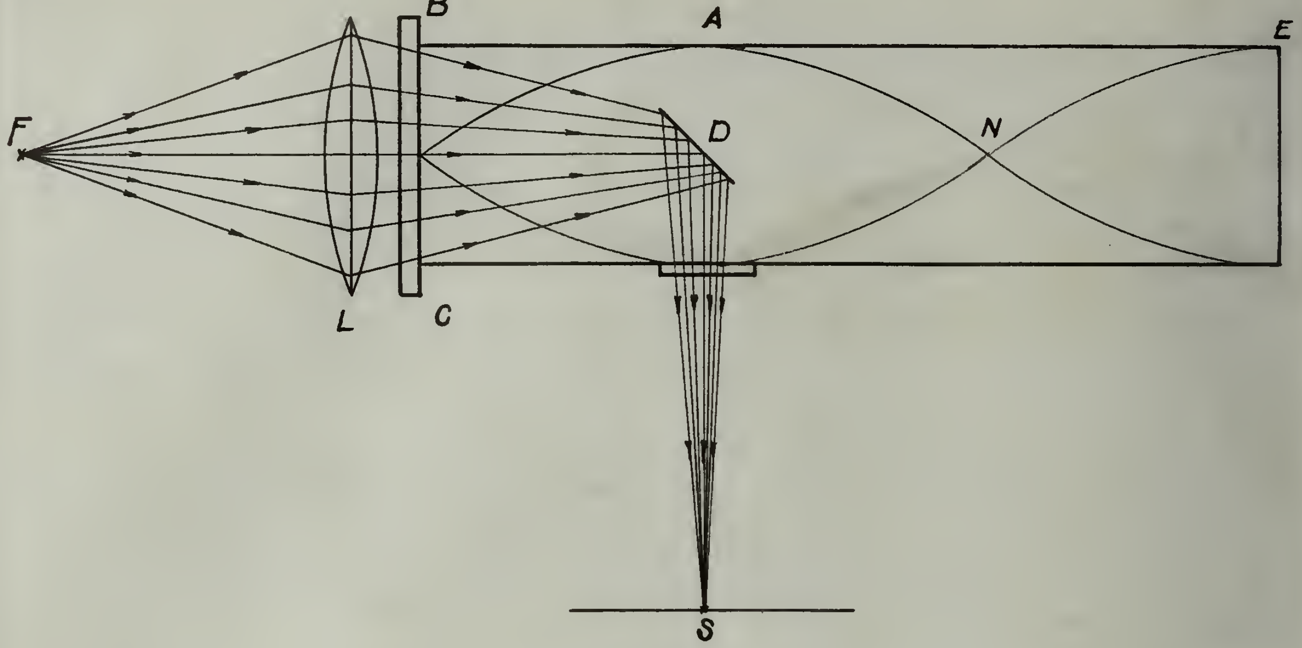


Fig. 1.

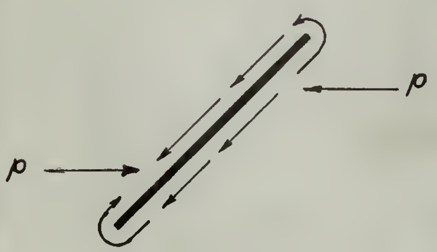


Fig. 2.

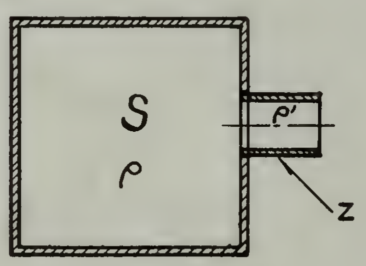


Fig. 3.

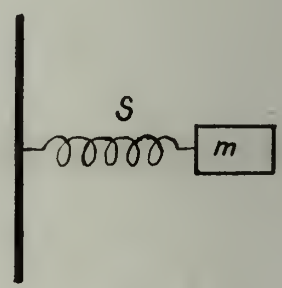


Fig. 4.

Z enlarged

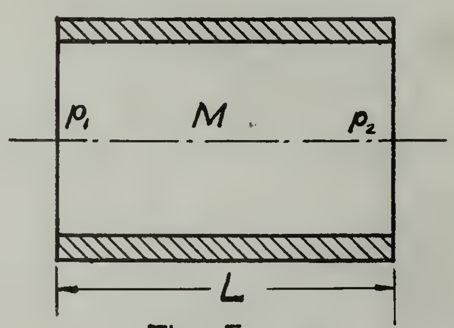


Fig. 5

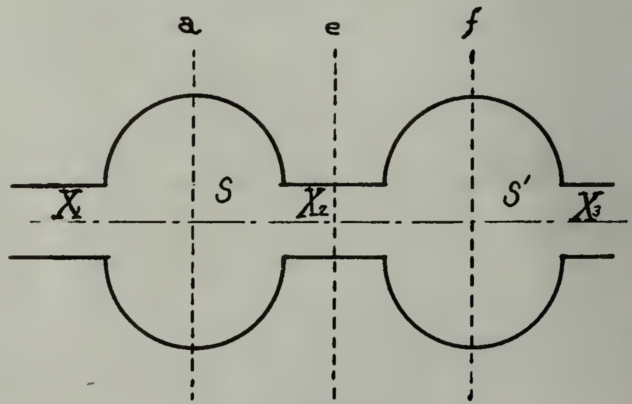


Fig. 6.

Consider the resonator(Fig.3) to be cylindrical, and represent the volume by S, length of neck by L, cross-sectional area of the neck by A, density of the air in the cylinder by ρ , and that in the neck by ρ'. Then the mass (m) of the gas (Barton, "Text-Book on Sound, Sec.240) in the neck, considered as in motion, would be

$$AL\rho'. \tag{2}$$

The condition represented here is, mechanically, similar to a spring with a mass, m, attached (Fig.4). The spring corresponds to the elasticity of the air in the cylinder where the motion is considered negligible, and the mass in motion to the mass of air agitated in the neck of the cylinder.

A calculation of the spring factor involves a consideration of changes in pressure and density (Fig.5). If the difference in pressure is p_1-p_2, then the work for a displacement of length L is

$$A(p_1-p_2)L = AdpL$$

or the force per unit displacement, s, would be

$$s = Adp. \tag{3}$$

To find a value for dp, we note first that

$$v = \sqrt{\frac{\text{elasticity}}{\text{density}}} = \sqrt{\frac{dp}{d\rho}} = \sqrt{\frac{\lambda p}{\rho}}$$

(Barton, "Text-Book on Sound", Sec.152), or

$$v^2 = \frac{dp}{d\rho} = \frac{\lambda p}{\rho}$$

and

$$dp = \lambda\, p \frac{d\rho}{\rho}. \tag{4}$$

To determine $\frac{d\rho}{\rho}$, we may consider the length of the neck L to be unity. This gives, initially, a total mass in the cylinder and neck of

$$(S+A)\rho .$$

If the gas be compressed from the neck into the cylinder, the mass may be represented as

$$S(\rho + d\rho)$$

or

$$(S+A)\rho = S(\rho + d\rho)$$

and

$$\frac{d\rho}{\rho} = \frac{A}{S}\,. \tag{5}$$

Substituting equations (3), (4), and (5) into (1), we obtain for τ, the period

$$\tau = 2\pi\sqrt{\frac{L\rho' S}{A\lambda p}}$$

or the frequency, N, is

$$N = \frac{1}{2\pi}\sqrt{\frac{c\lambda p}{\rho' S}} = \frac{v}{2\pi}\sqrt{\frac{c}{S}}$$

where c, the conductivity expression, is substituted for the fraction A/L.

The mathematical treatment of the double resonator as given by Lord Rayleigh (Theory of Sound, Vol.II, Sec.310) shows that the pitch may be calculated in much the same way.

In the solution of his equations, two types of motion are represented. In the one, a node is formed at e (Fig.6) and the result is the same as though there was no communication between the chambers. The motions of the air, X_1 and X_3, are opposite. In the other equation, the motions of X_1 and X_3 are in the same direction but always opposite to the motion of X_2. This would seem to represent a condition for a node at a and f (Fig.6), since the air is always in opposite directions between the consecutive necks. Moreover, it is shown that such a resonator has two pitches, depending upon the relations of the volumes, S and S', to the necks.

In a recent article (Lord Rayleigh, Phil.Mag. Vol.36, Sept. 1918, p 231), he points out advantages of having a small S', since, by making S' sufficiently small, it should be possible to make the instrument more sensitive. The pitch of the instrument actually used is calculated from the formula to be approximately 510 vibrations per second. This follows from the general equation by applying the conditions and dimensions for the instrument under test. The simplified expression is

$$N = \frac{a}{2\pi}\sqrt{C_2\left(\frac{1}{S'} + \frac{1}{S}\right)} \quad .$$

Since S is very large as compared to S', 1/S may be neglected compared with 1/S', and the expression becomes

$$N = \frac{a}{2\pi}\sqrt{\frac{C_2}{S'}}$$

which is the formula for a single resonator, where a is the velocity of sound.

IV DESCRIPTION OF APPARATUS

The general type of instrument used here in sound measurements is shown in Fig.7. The double resonator part consists of two brass cylinders, A and B, connected by a narrow circular neck. The disc is mounted in this connecting neck and is suspended by a long, delicate quartz fibre so that it is easily turned. Light from a tungsten lamp passes through the lens, L, and is reflected by the rotating disc to the circular scale N, graduated in degrees. When sound enters the cylinder A at C, it causes a small rotation of the disc with a consequent movement of the spot of light on the scale.

The acoustic galvanometer is similar to the instrument just described. A telephone receiver, actuated by an alternating current,

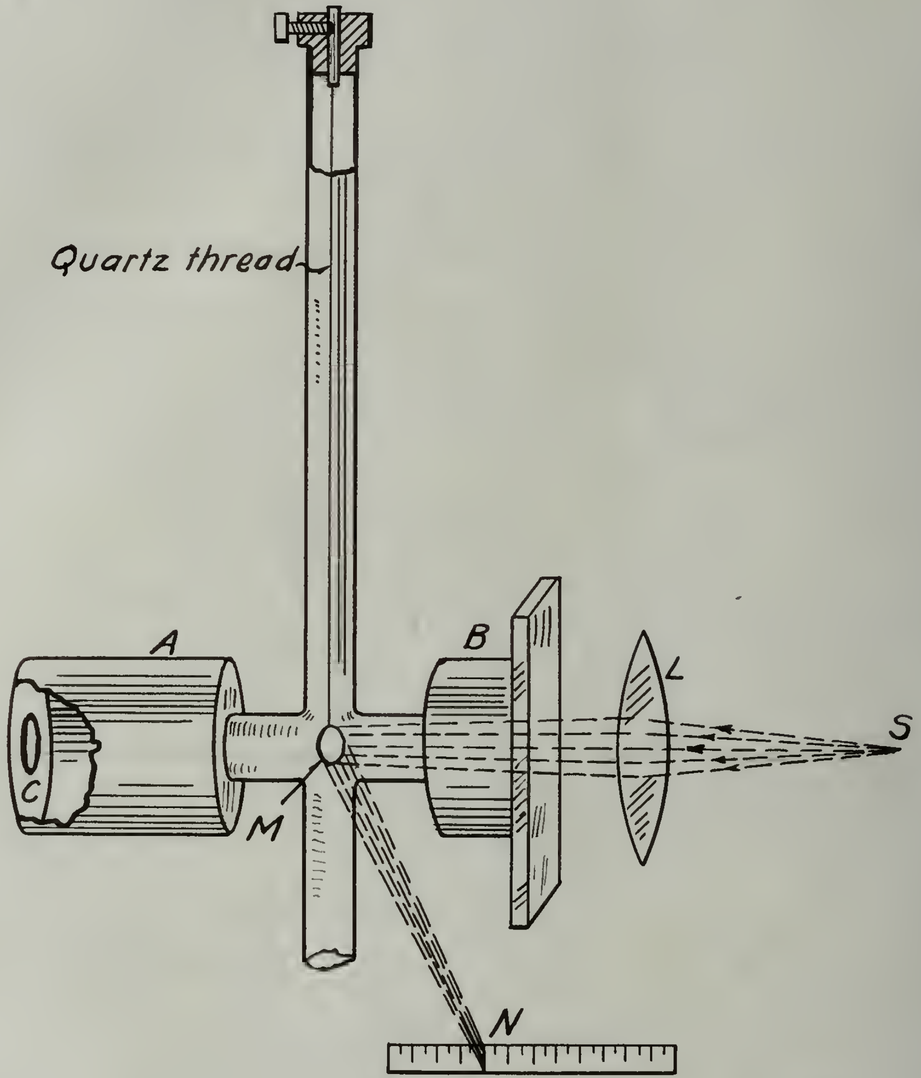


Fig. 7

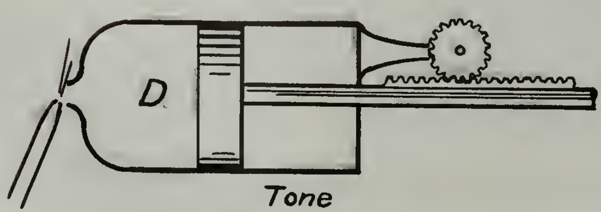


Fig. 8

acts as a source of sound and replaces cylinder A. All joints were sealed as effectively as possible, the object being, to make the instrument insensible to external sources of sound.

Two sources of alternating current were used at different times to secure constant pitch and small enough intensity to give a readable deflection of the disc.

For one source of alternating current, the piston of a tone variator was replaced (Fig.8) by a telephone receiver. If air is supplied now to such an instrument, the varying pressure due to the stationary sound waves will cause a small movement of the telephone plate and thus create induced alternating current of small intensity. Such an instrument will be called a receiver tone variator.

In the usual set-up for this source of current compressed air (Fig.9) was allowed to pass into a constant pressure air tank, through a stop cock to regulate the pressure, as indicated by the manometer, m, to the receiver tone variator. The receiver was connected to the acoustic galvanometer, g, through a resistance, R, in series, and a resistance, s, in shunt. The receiver tone variator was kept in a well padded box and the pitch was determined by tuning forks.

A Siemens and Halske high frequency machine was used for the other source of alternating current. Fig.10 pictures the apparatus. Current from the machine passed through a high resistance R. A portion of this current was sent through a bridge wire and hot wire ammeter in series. A part of the bridge wire current, as indicated by the portion of the wire, s, was sent through the acoustic galvanometer, g. As the frequency was changed, the current through the

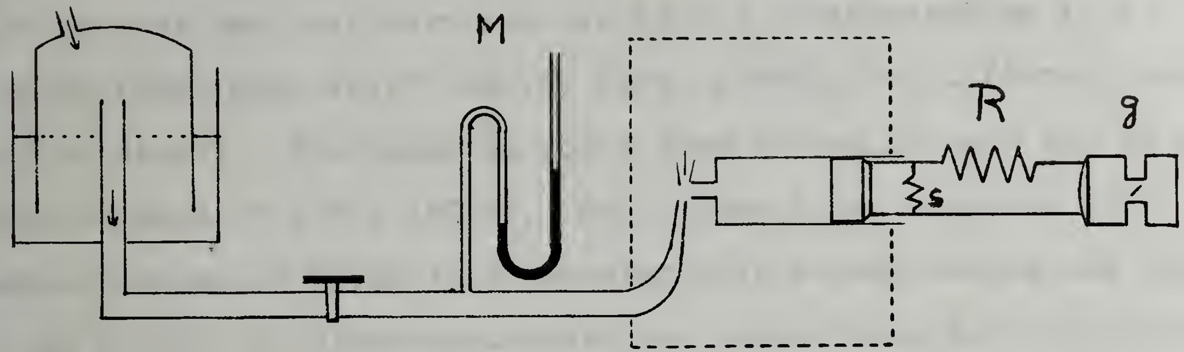


Fig 9

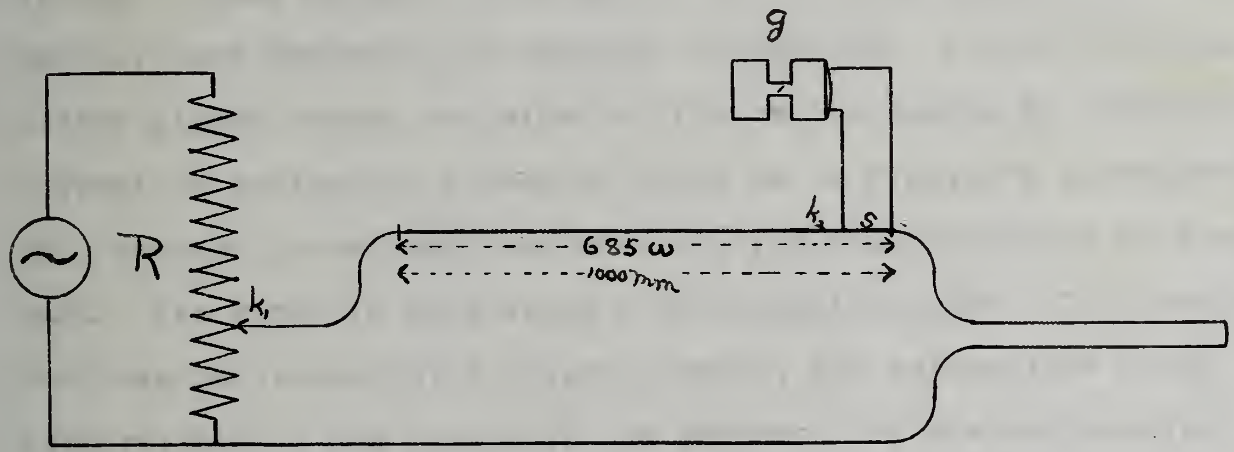


Fig 10

Fig 9

Fig 10

bridge wire was kept constant by a sliding contact, k_1.

The alternating current generated was too small to actuate our ordinary alternating current ammeters. Therefore, a special hot wire ammeter was made very similar to one constructed by J. A. Fleming (Phil.Mag. Vol.7, Ser.6, 1904, p 595), but differing somewhat in detail. Two brass supports were placed at each end of a block of wood, 5 x 5 x 100 cm. From these brass supports two manganin wires of 0.003 inch diameter were strung across the top of the block, the distance between the wires being 2.5 millimeters. The tension on these wires was made adjustable by means of suitably designed springs. The wires were connected at one end so that the alternating current passed through both wires. A fine steel loop wire, placed in the center of either wire, was used as a spring. These springs were adjusted so that when the wires were heated, they deflected in opposite directions. A tiny silvered mirror placed across the wires at the center served to indicate the current by deflecting a beam of light as in Fleming's instrument. This ammeter proved very satisfactory for the particular work at hand. Its range is from about 5 to 50 milliamperes. The instrument was calibrated with direct current, the deflections being proportional to the square of the current. In the calibration, 2.1 volts produced a deflection of 1.65 centimeters; 4.2 volts a deflection of 5.7; 6.3 volts a deflection of 11.0 centimeters; and 8.35 volts a deflection of 19.6 centimeters, the resistance of the ammeter being 201.4 ohms.

V EXPERIMENTAL

Although sealed against external sound waves, it was found early in the work that the acoustic galvanometer responded readily

to any sound disturbance. The effect of external sound was so great that a few measurements were taken to determine the nature of the disturbance. A tone variator, operated at constant pressure, was placed in the room and the deflections noted for various pitches. The results are shown in Fig.11. This curve was displaced to the left or right for different positions of the tone variator, showing the change of effect due to a new set of stationary waves. Hence, it was important to observe that no external sound be present while studying the instrument with alternating current. Any necessary source of sound was boxed in (See Fig.9) or generated in another room.

Preliminary tests of the apparatus (F.R. Watson, Am.Phys.Rev. Vol.13, Apr.1919, p 287; or Elec. World, Vol.73, May 17,1919, p 1044 , "On measurement of small alternating current by means of a Rayleigh resonator") indicated that the galvanometer was sensitive to quite small currents and that at certain frequencies, it exhibited greater sensitivity.

With these tests in mind, the receiver tone variator arrangement first suggested itself for determining the characteristics of the galvanometer. Even with this source of alternating current, a shunt resistance, s, was necessary if resistance, R, was to be kept reasonably small (Fig.9). Of the results obtained, those of Table I are representative, the corresponding curve being shown by Fig. 12. The deflections were steady and constant in all cases. In a later duplication of the result obtained here by another method, it will be found that the peak of greatest deflection is a little farther to the right than indicated here.

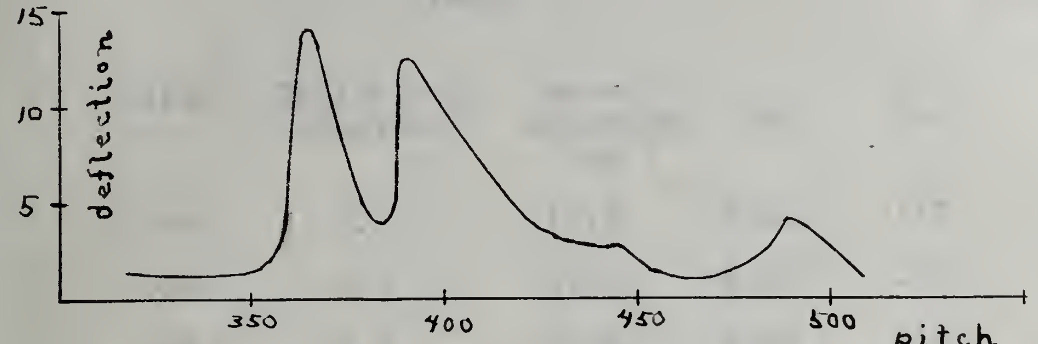


Fig 11

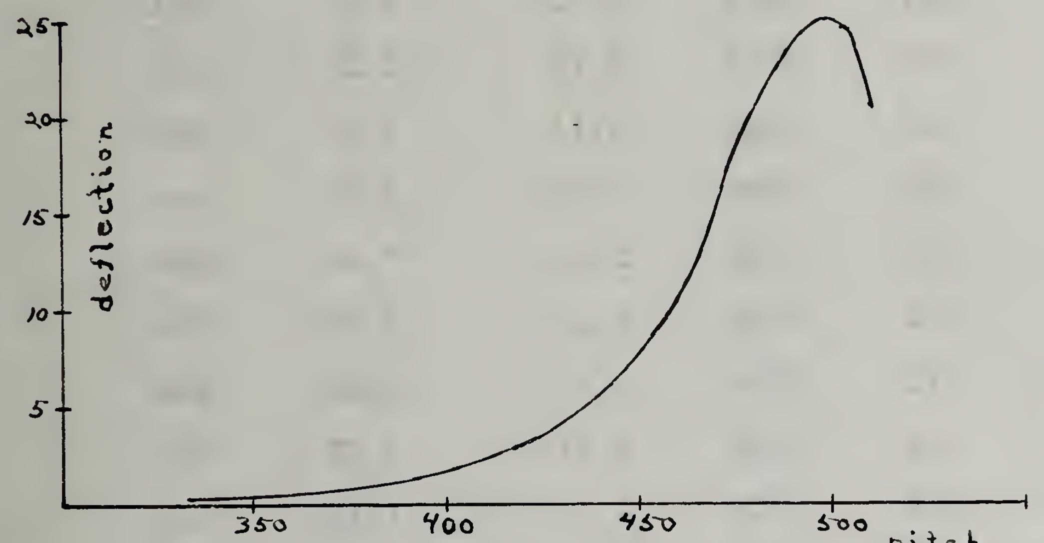


Fig 12

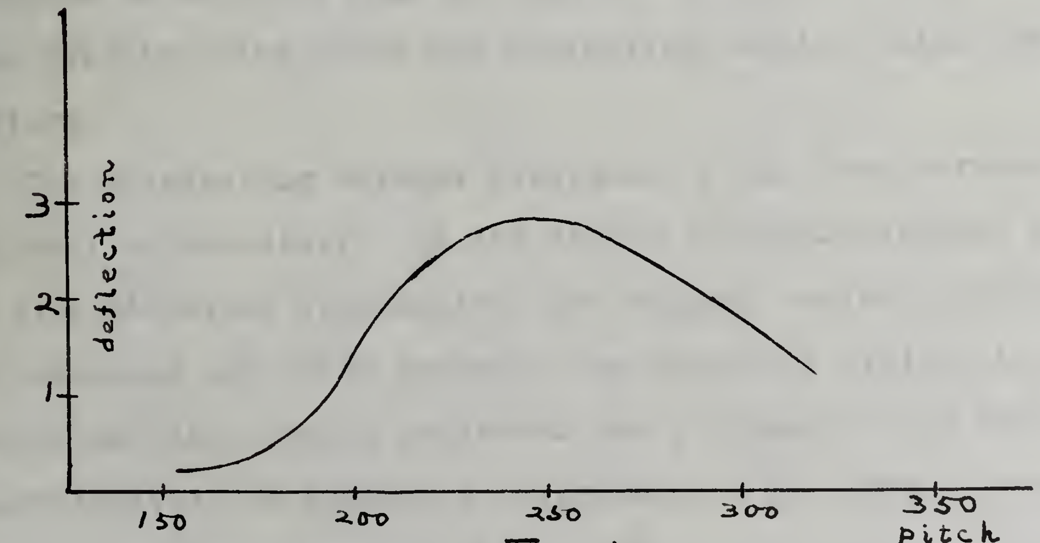


Fig 13

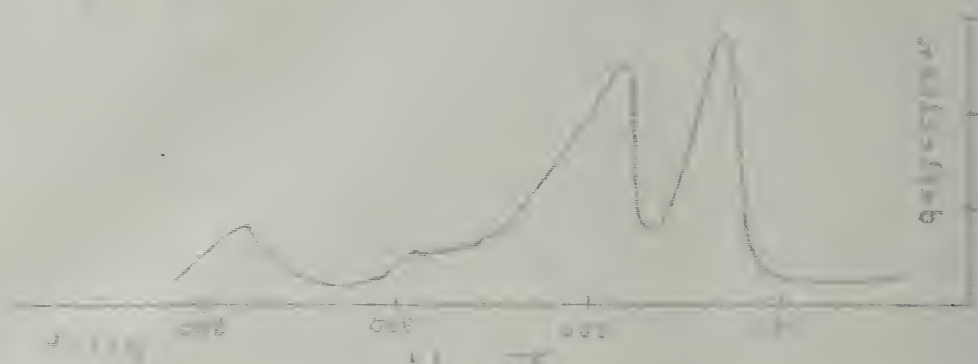


Fig 11

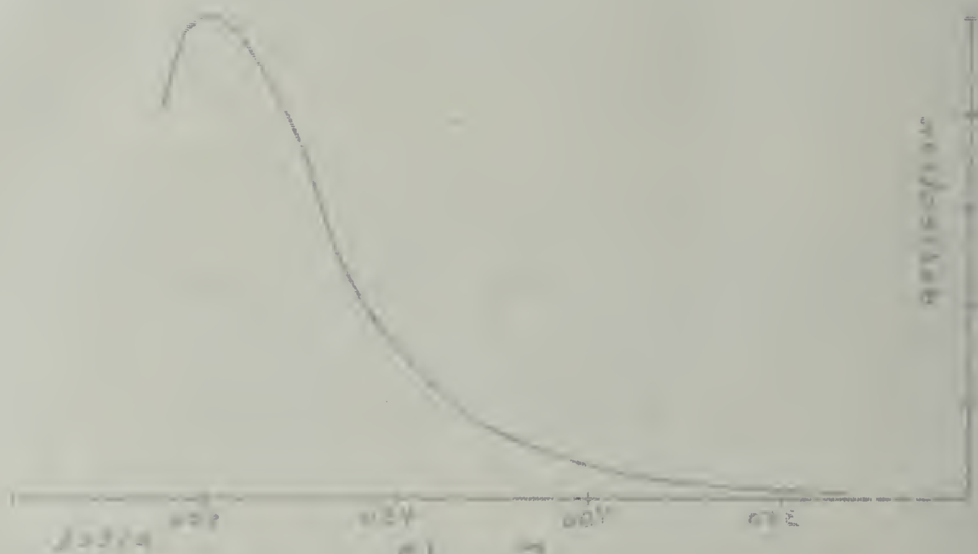


Fig 12

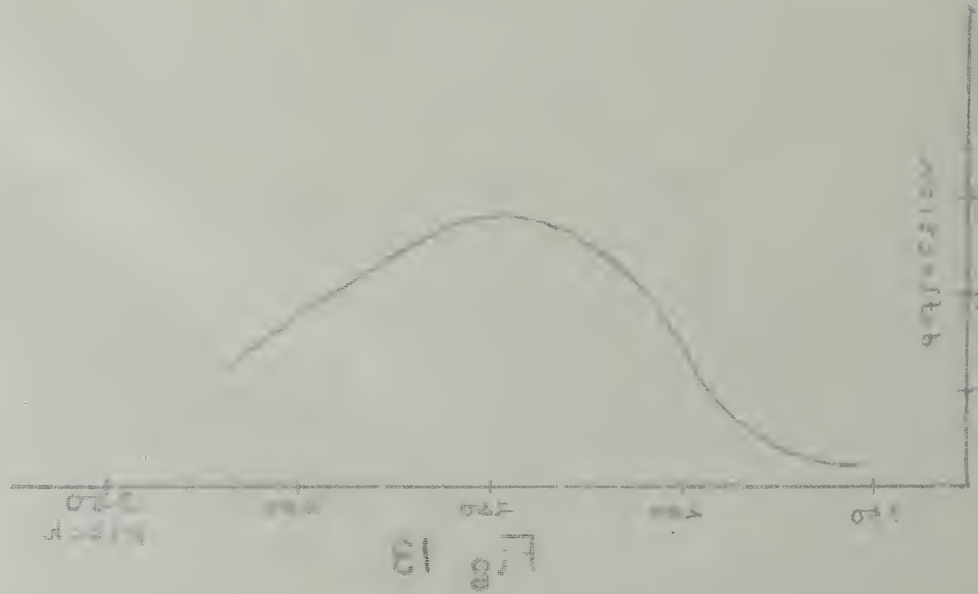


Fig 13

TABLE I

Pitch	Deflection (degrees)	Water pressure (cm.)	R	s
335	0.1	11.0	8000	110
350	0.2	11.0	8000	110
365	0.5	11.0	8000	110
380	1.0	11.0	8000	110
395	1.5	11.0	8000	110
410	2.5	11.0	8000	110
425	3.7	11.0	8000	110
440	5.9	11.0	8000	110
455	9.7	11.0	8000	110
470	16.0	11.0	8000	110
485	22.6	11.0	8000	110
500	25.1	11.0	8000	110
511	21.1	11.0	8000	110

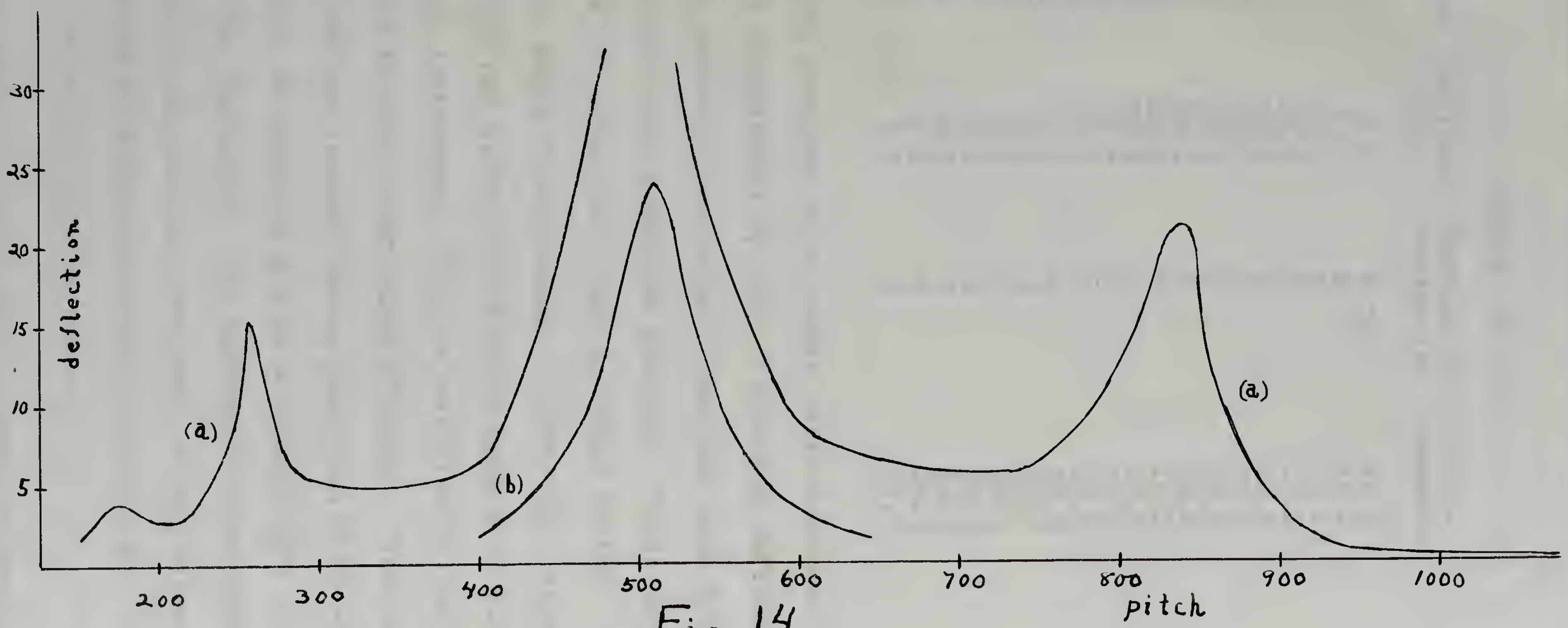
Another curve representing the relation between pitch and deflection is shown in Fig.13. This was obtained with the receiver tone variator, the pitch and deflection, again, being the variable factors.

The alternating current furnished by the tone variator was not entirely satisfactory. As the volume of the instrument was varied to give different frequencies, the current varied in intensity due to resonance and other causes. The range was limited to about an octave and the current generated was too small to be measured quantitatively by available instruments. It served, however, for preliminary measurements.

A more satisfactory current was obtained with a Siemens and Halske high frequency machine. The method followed here has been described under Fig.10. With this source of alternating current, a relation between the frequency or pitch and the corresponding deflection of the acoustic galvanometer was obtained. The data is given in Table II, and the curve in Fig.14.

TABLE II (a)

Pitch	Deflec-tion	Portion of bridge (s)	milli-amperes
150	1.5	15 cm.	19.5
175	3.8	15	19.5
200	2.7	15	19.5
225	3.5	15	19.5
235	6.3	15	19.5
250	9.5	15	19.5
256	15.4	15	19.5
288	5.9	15	19.5
350	5.0	15	19.5
400	6.5	15	19.5
426	14.2	15	19.5
450	19.2	15	19.5
480	32.2	15	19.5
500	off	15	19.5
512	off	15	19.5
520	off	15	19.5
530	31.2	15	19.5
540	24.2	15	19.5
550	20.2	15	19.5
605	8.3	15	19.5
645	6.5	15	19.5
700	5.7	15	19.5
750	6.0	15	19.5
775	8.5	15	19.5
800	12.7	15	19.5
810	14.5	15	19.5
820	17.5	15	19.5
830	20.7	15	19.5
840	21.3	15	19.5
850	17.8	15	19.5
878	6.8	15	19.5
935	0.9	15	19.5
990	0.4	15	19.5
1080	0.2	15	19.5
1160	0.0	15	19.5



deflection
30
25
20
15
10
5
(a)
(b)
(a)
200
300
400
500
600
700
800
900
1000
pitch

Fig 14

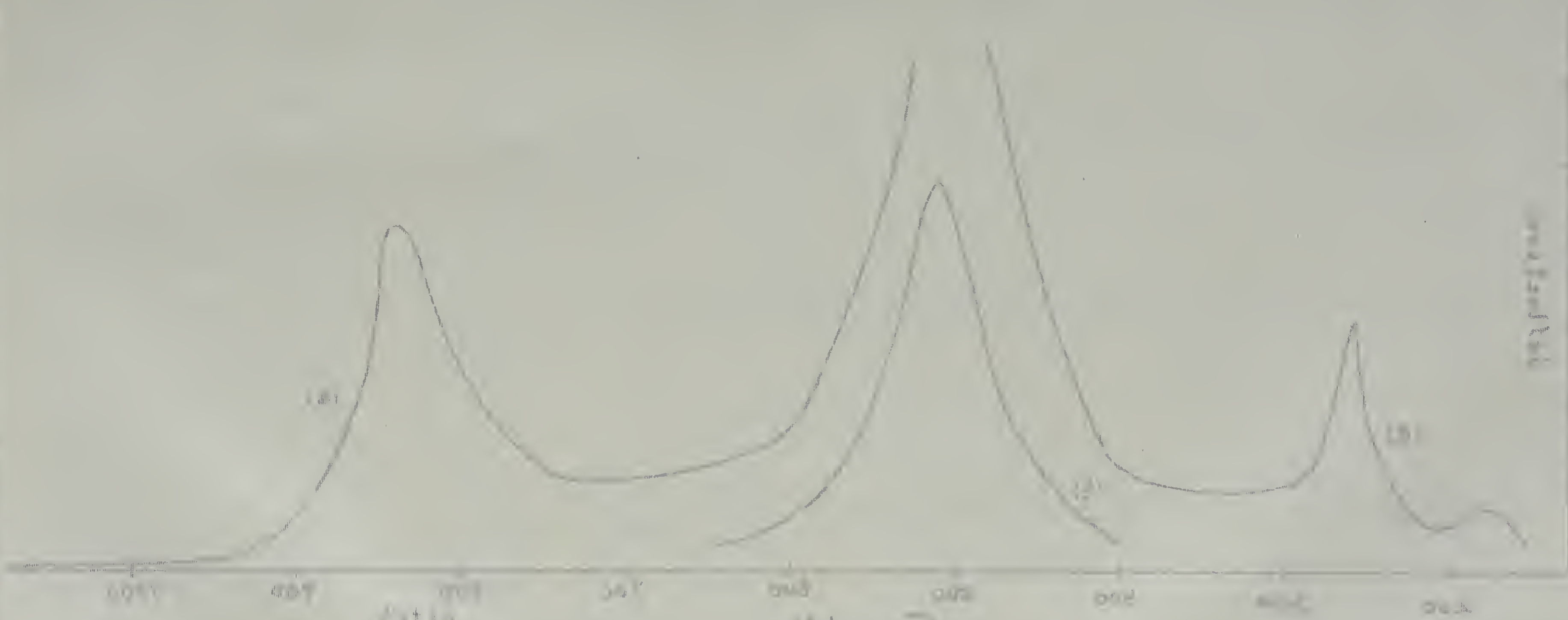


Fig 14

TABLE II (b)

Pitch	Deflection	Portion of bridge (s)	milliamperes
400	2.0	8 cm.	19.5
450	6.7	8	19.5
470	10.0	8	19.5
480	15.6	8	19.5
490	18.2	8	19.5
500	22.0	8	19.5
505	23.0	8	19.5
510	24.0	8	19.5
515	23.2	8	19.5
520	22.4	8	19.5
530	17.0	8	19.5
540	13.7	8	19.5
550	10.7	8	19.5
560	8.3	8	19.5
570	6.9	8	19.5
580	5.1	8	19.5
590	4.5	8	19.5
600	4.3	8	19.5
645	1.7	8	19.5

This curve consists of a broken curve represented by (a), and a second curve represented by (b). Since the deflection went off the scale in one place for Curve (a), readings were taken over this particular point with a smaller current. These readings are noted by the curve (b), the data being in Table II (b).

The curve shows three maxima. Since this largest maximum is at 510 vibrations per second, this would appear to show the natural period of the instrument. This is verified by the calculations shown earlier in the report under "Theory". The smaller maximum at 256 vibrations per second, having practically one-half the frequency of 510, is probably due to a stimulation of the natural vibration of the resonator. The maximum at the frequency of 840 is probably due to the natural frequency of the telephone plate, since these are tuned to frequencies approximately 800 to 900 per second.

It was indicated early in the article that the acoustic

galvanometer has possibilities as a means of measuring very small alternating current. The present work not only confirms this view, but also adds to the undeveloped possibilities. The resistance of the receiver in the acoustic galvanometer was 400 ohms. Hence, from Table II, a calculation of results will show the extreme sensitiveness of this particular instrument when figured in the usual units to be of the order 5.7×10^{-9} amperes/mm. Such a degree of sensitiveness would seem, at first, rather surprising. It is important to note that the instrument is entirely mechanical in operation and is not broken down by an over-load like most instruments of this delicacy in measurement. The deflection given for any current value is steady and constant at all times. The one point of possible weakness may be in the characteristics of the receiver itself.

No definite work has been done toward the calibration of the acoustic galvanometer for the measurement of alternating current. It was found that the calibration curve for any particular pitch was not quite a parabola. Fig.15 shows such a curve for a pitch of 350 vibrations per second.

A comparison of the extreme sensitiveness of the acoustic galvanometer and the audibility current of a telephone receiver shows each to be about the same in order of magnitude. To make this test, a receiver tone variator (Fig.9) was connected in series with the acoustic galvanometer and 100,000 ohms resistance; $s = \infty$. The pitch was varied from 350 to 535 vibrations per second. The curve for this data is shown in Fig.16, the maximum being 24.6° at 510 vibrations per second. A telephone receiver was faintly audible when substituted for the galvanometer at the pitch of 510 vibrations per second.

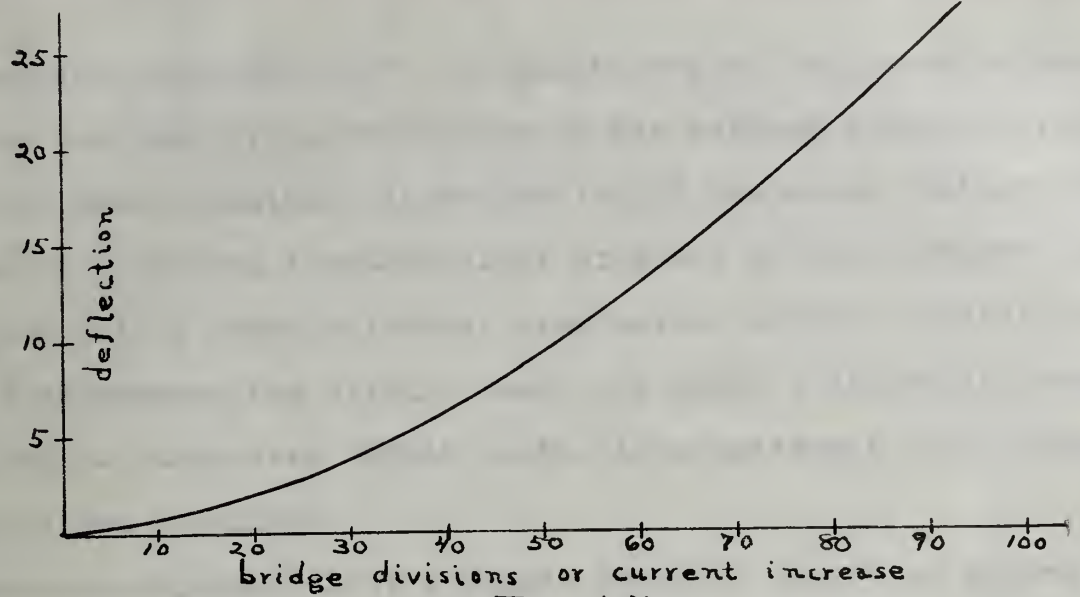


Fig 15

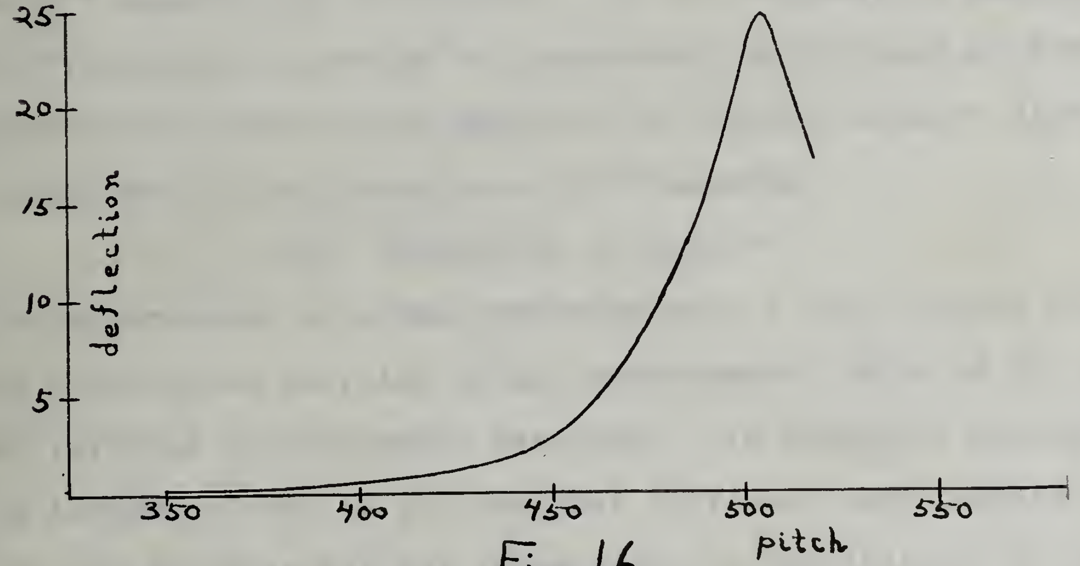


Fig 16

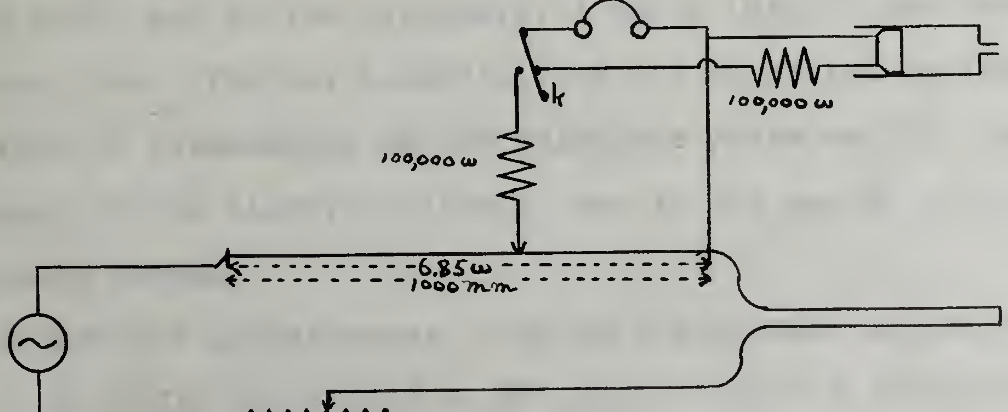


Fig 17

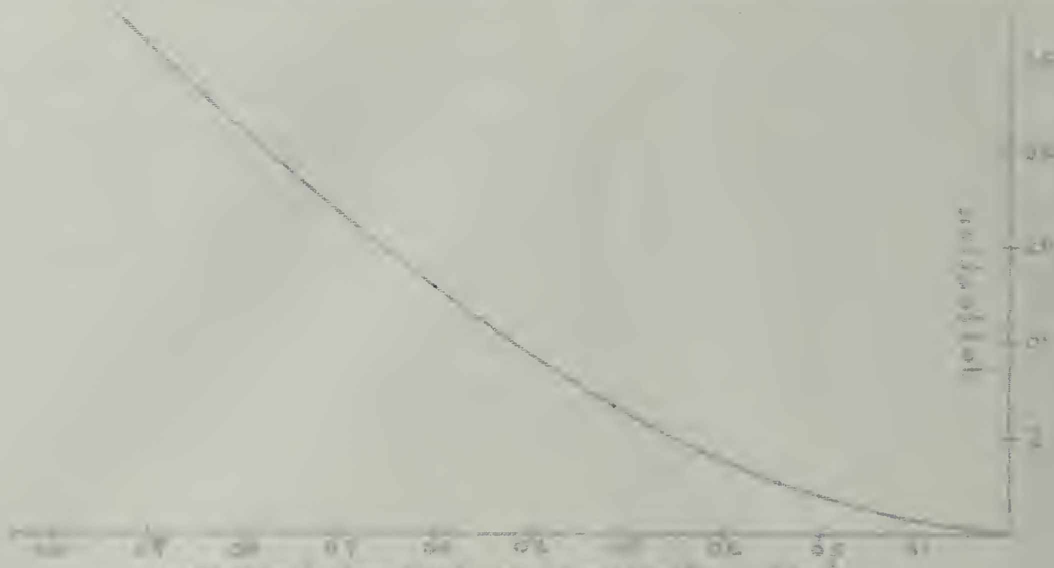


Fig 15

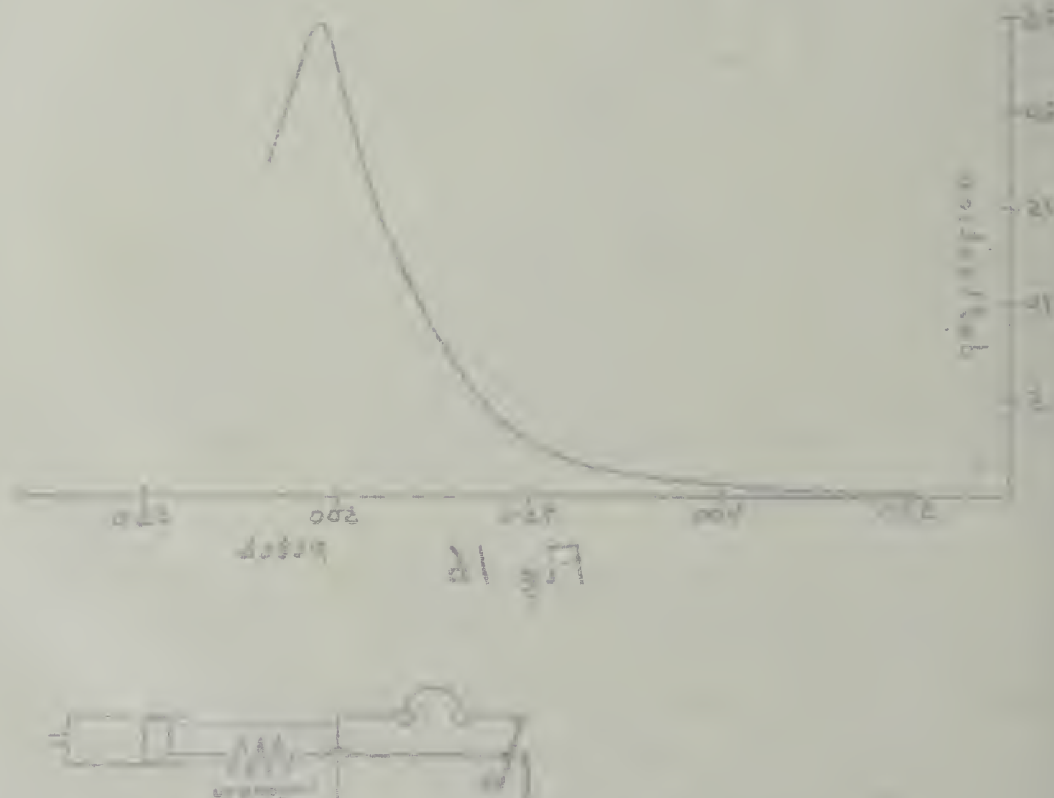


Fig 16

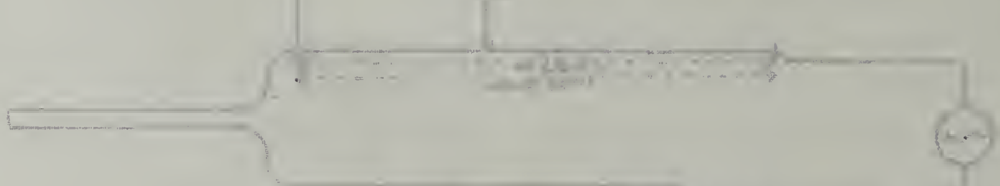


Fig 17

Another calculation of the sensitivity of the acoustic galvanometer was made by an estimation of the voltage produced by the receiver tone variator. An estimation of the above voltage was obtained by comparing the audibility produced by the receiver tone variator with a known potential drop across another similar circuit. Fig.17 represents the circuit used. By quickly depressing the contact key, a comparison within quite close agreement for different readings was obtained.

When calculated, as if a simple circuit, this test showed the sensitiveness of the acoustic galvanometer to be of the order 8.0×10^{-9} amperes per millimeter. In this connection Kennelly's tests ("Telephone Apparatus" by Shepardson, p 59) show a telephone receiver to be sufficiently sensitive to produce audible signals from a current of the order 4.4×10^{-8} amperes.

VI DISCUSSION OF RESULTS

The experiments have been extended over a very limited portion of the field to be included in any experimental study of the principles involved in the double resonator. In the brief discussion of the theory, it may be noticed that there are many possibilities open to the experimenter for increasing the sensitivity of the instrument. The effects of varying the size and shape of the connecting neck, and of the cylinders, A and B (Fig.7) are important considerations. Further possibilities are suggested in the coordination of frequencies of the telephone plate and the resonator, the tuning of the electric circuit, and in the use of a more sensitive quartz thread.

The acoustic galvanometer, used in the present experiments, appears to differ but little in principle from the resonator open

at one end. Consideration of Fig.1 and Fig.6 would indicate that the most sensitive form would be obtained with the glass plate in B (Fig.6) at a node and the receiver diaphragm in A at a position near the node. This would give approximately a half wave-length between the two extreme ends of the double resonator. It is not probable that the present instrument, made up with no particular dimensions in view, approaches the most sensitive form. That it may be made more sensitive should, therefore, be indicated.

The wave form of the sound generated has necessarily been distorted. This fact is well appreciated; and for the present calculations on sensitiveness, it was thought not best in the limited time available to study the wave form and circuit in detail. It is shown, however, that the instrument is very sensitive to any wave form, and that the deflection is steady and constant so long as the source of sound remains constant.

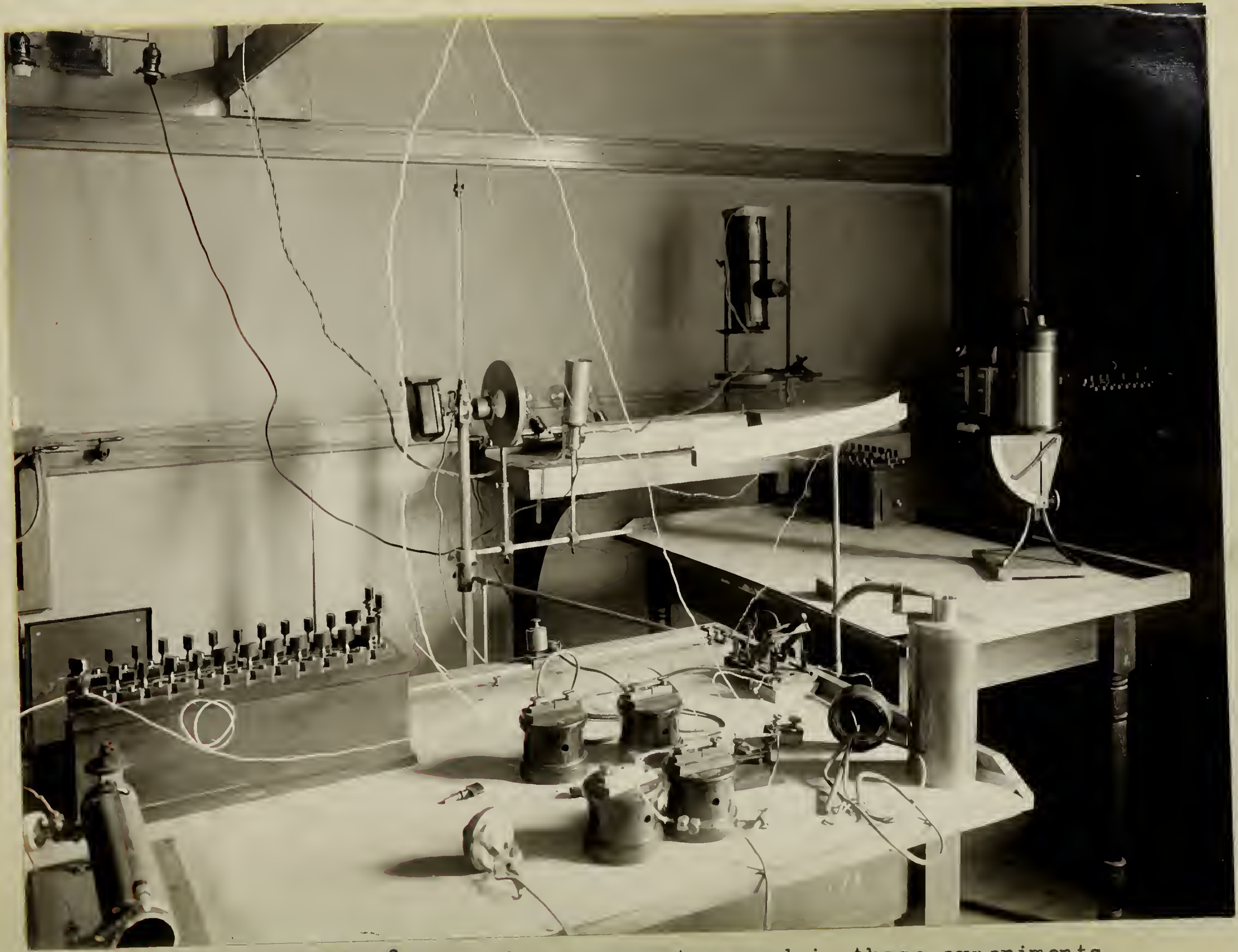
VII APPLICATIONS

An instrument that will give quantitative measurements of sound intensity of very small magnitude has varied applications. In addition to measuring small alternating currents, it has already been used to obtain measurements on the transmission of sound through partitions (F.R. Watson, Phys.Rev. Vol.7, p 125, 1916), and can be extended to practical measurements of transmission and reverberation of sound in buildings. It would be useful in psychological tests where quantitative measurements of sounds are desired. It appears promising for use in telephone research where it would measure the actual performance of telephone receivers with varying conditions for current, resistance and other electrical factors.

VIII SUMMARY

Experimental test of the Rayleigh double resonator, adapted by addition of a telephone receiver, gave a measure of alternating current. The particular resonator investigated gave responses to alternating currents of the order 10^{-9} amperes at the frequency 510 vibrations. It seems likely that alterations of the controlling factors will give a greater sensitivity.

In conclusion, the author desires to acknowledge the assistance of various members of the Department of Physics, especially of Professor F.R. Watson for the kindly guidance and interest given at all times, and of Professor A.P. Carman for the generous use of the facilities of the Laboratory.



A general view of part of the apparatus used in these experiments.